Measurement of di-jet event cross sections at $\sqrt{s} = 13$ TeV with CMS data

DPG Conference Dortmund 2021

3D Differential Jet Multiplicity cross section (N_{jets},$\Delta\phi_{\text{dijet}}$, p_T^{max})

2D Differential cross section as function of p_T of first 4 leading jets (p_T^i , N_{jet}^i)

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Introduction

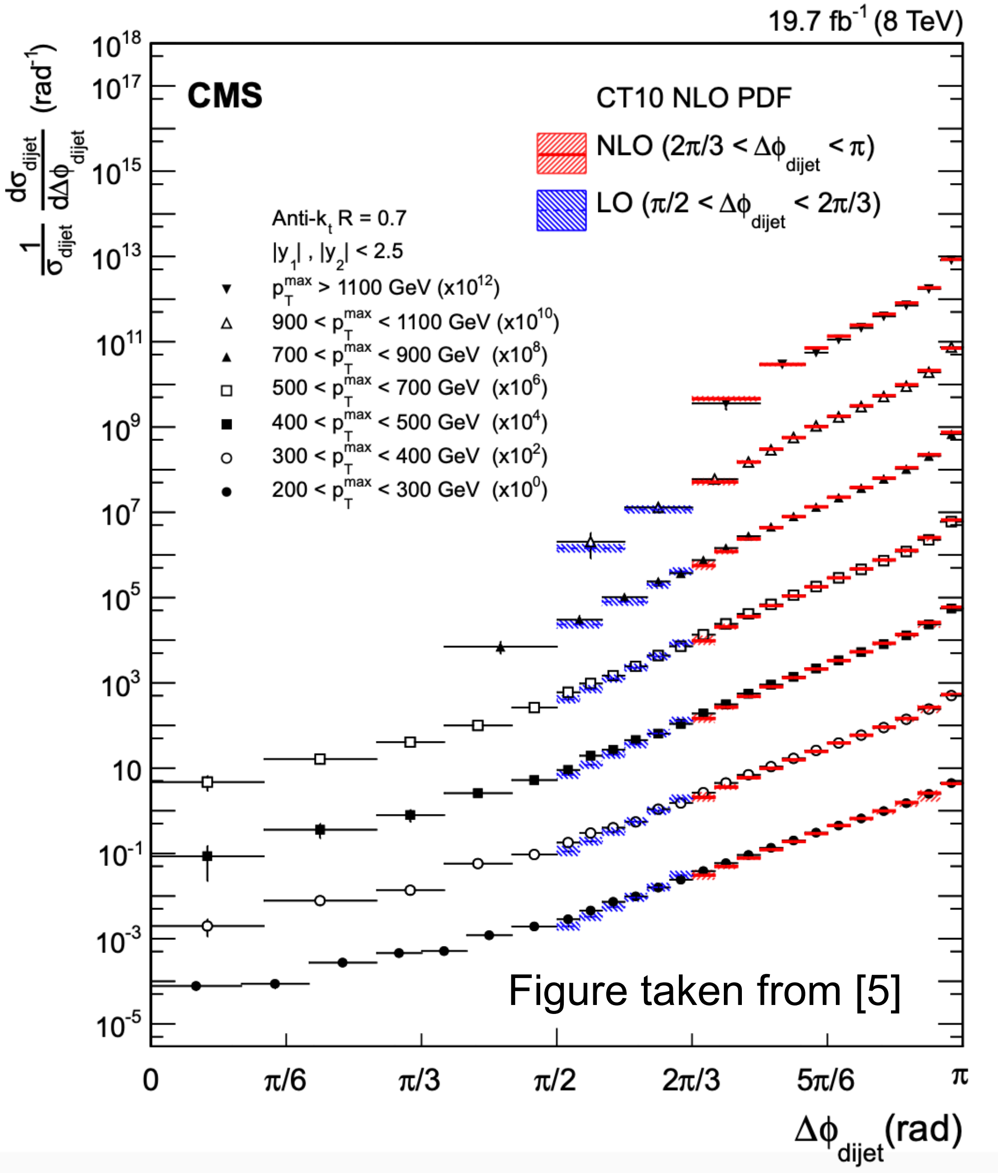
Previous measurements and motivation

Azimuthal correlations in high p_T dijet events have been already measured by DØ Collaboration in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV [1,2], pp collisions by ATLAS Collaboration at $\sqrt{s} = 7$ TeV [3], and by CMS Collaboration at $\sqrt{s} = 7, 8, 13$ TeV [4-7].

Effects of higher order contributions to the dijet system decorrelation were observed, but still information on how the decorrelation is build is missing.

Detailed investigations needed:

- Jet multiplicity in bins of $\Delta\phi_{\text{dijet}}$ and p_T^{max}
- p_T spectra of first four leading jets



[1] https://doi.org/10.1103/PhysRevLett.94.221801
[2] https://doi.org/10.1016/j.physletb.2013.03.029
[3] https://doi.org/10.1103/PhysRevLett.106.172002
[4] https://doi.org/10.1103/PhysRevLett.106.122003
[5] https://doi.org/10.1140/epjc/s10052-016-4346-8
[6] https://doi.org/10.1140/epjc/s10052-018-6033-4
[7] https://doi.org/10.1140/epjc/s10052-019-7276-4

Data and MC analysis

Definition of the observables

- Jet multiplicity in bins of $\Delta\phi_{\text{dijet}}$ and p_T^{max} :
  - N_{jets} binning [=2,=3,=4,=5,=6, >=7]
  - $\Delta\phi_{\text{dijet}}$binning [0,150,170,180] degrees
  - p_T^{max} binning [200,400,800,13000] GeV

$$\frac{d^3\sigma}{dp_T^{max}\, d\Delta\phi_{\text{dijet}}\, dN_{\text{jets}}}$$

- p_T spectra of first four leading jets:

$p_T^{\text{leading jet}}$ ($N_{jets} \geq 2$) [200,.., 2000] GeV

$p_T^{\text{2nd leading jet}}$ ($N_{jets} \geq 2$) [100,.., 2000] GeV

$p_T^{\text{3rd leading jet}}$ ($N_{jets} \geq 3$) [50,.., 967] GeV

$p_T^{\text{4th leading jet}}$ ($N_{jets} \geq 4$) [50,..,638] GeV

$$\frac{d^2\sigma}{dN^i_{\text{jets}}\, dp^i_T}$$

Data and MC analysis

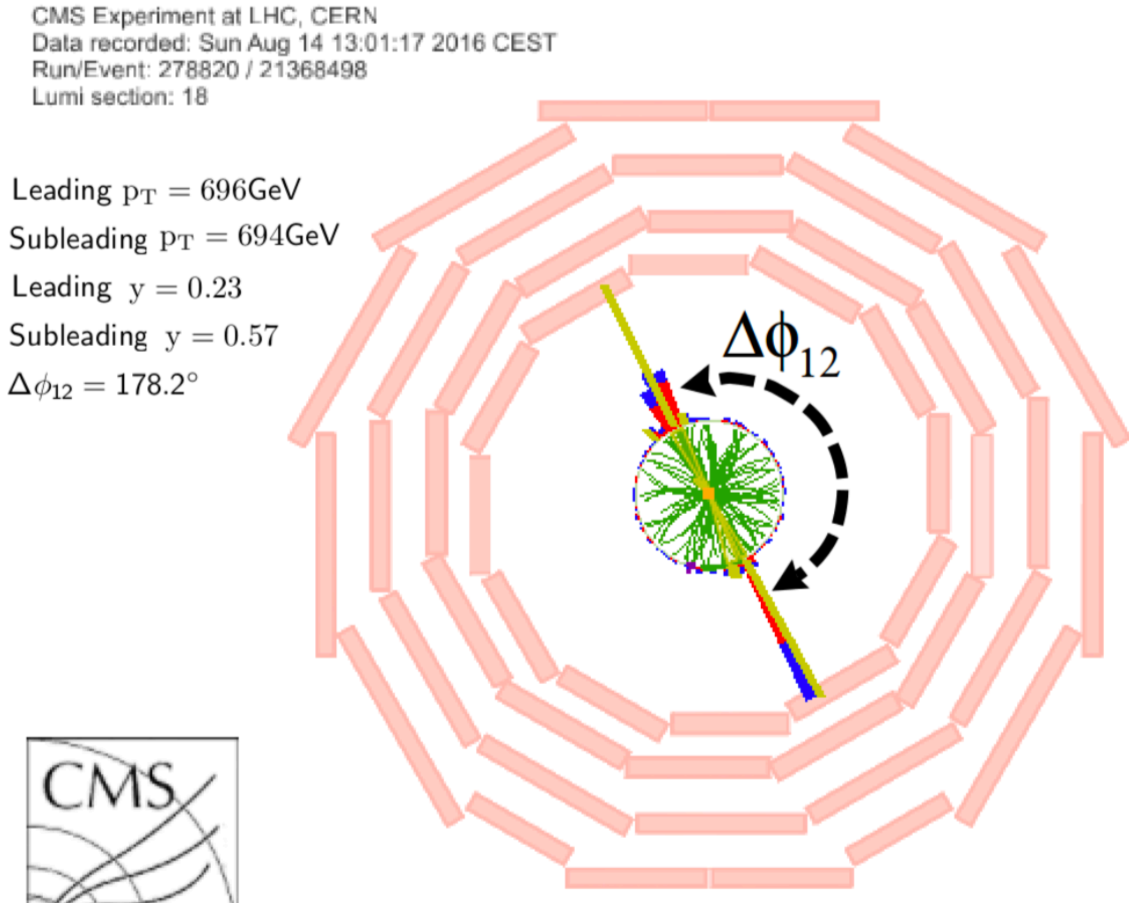
Event selection

First, we select PFchs jets with $|y^{\mathrm{jet}}| < 3.2$ and $p_T^{\mathrm{jet}} > 20$ GeV
Then we apply the following:

- $p_T^{\mathrm{jet1(jet2)}} > 200(100)$ GeV and $|y^{\mathrm{jet1,\ jet2}}| < 2.5$
- jet1 and jet2 fulfill jet quality criteria (detector level only)
- MET fraction < 0.1 (detector level only)

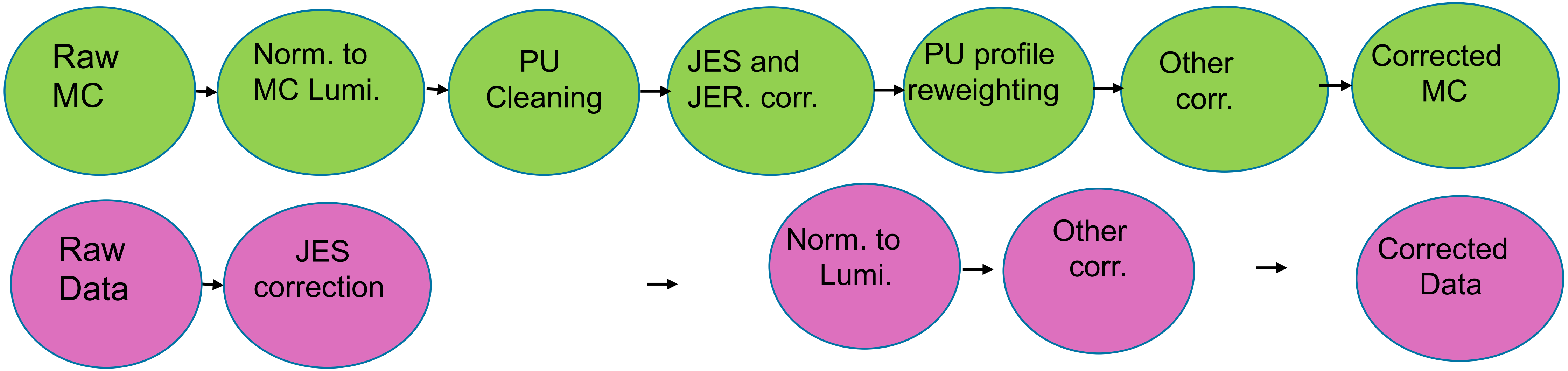
Cuts on extra jets:

- $p_T^{jet} > 50\ GeV$ and $|y^{jet}| < 2.5$
- select jets pass jet quality criteria (detector level only)



Data and MC analysis

Corrections applied to data and MC



- Modular workflow is followed, factorizing each correction.
- The remaining corr. (Other corr.) are MET filters and Hot zones (plus prefiring for MC)
- We use Legacy data and LO MC samples (MadGraph, Pythia8, Herwig++)

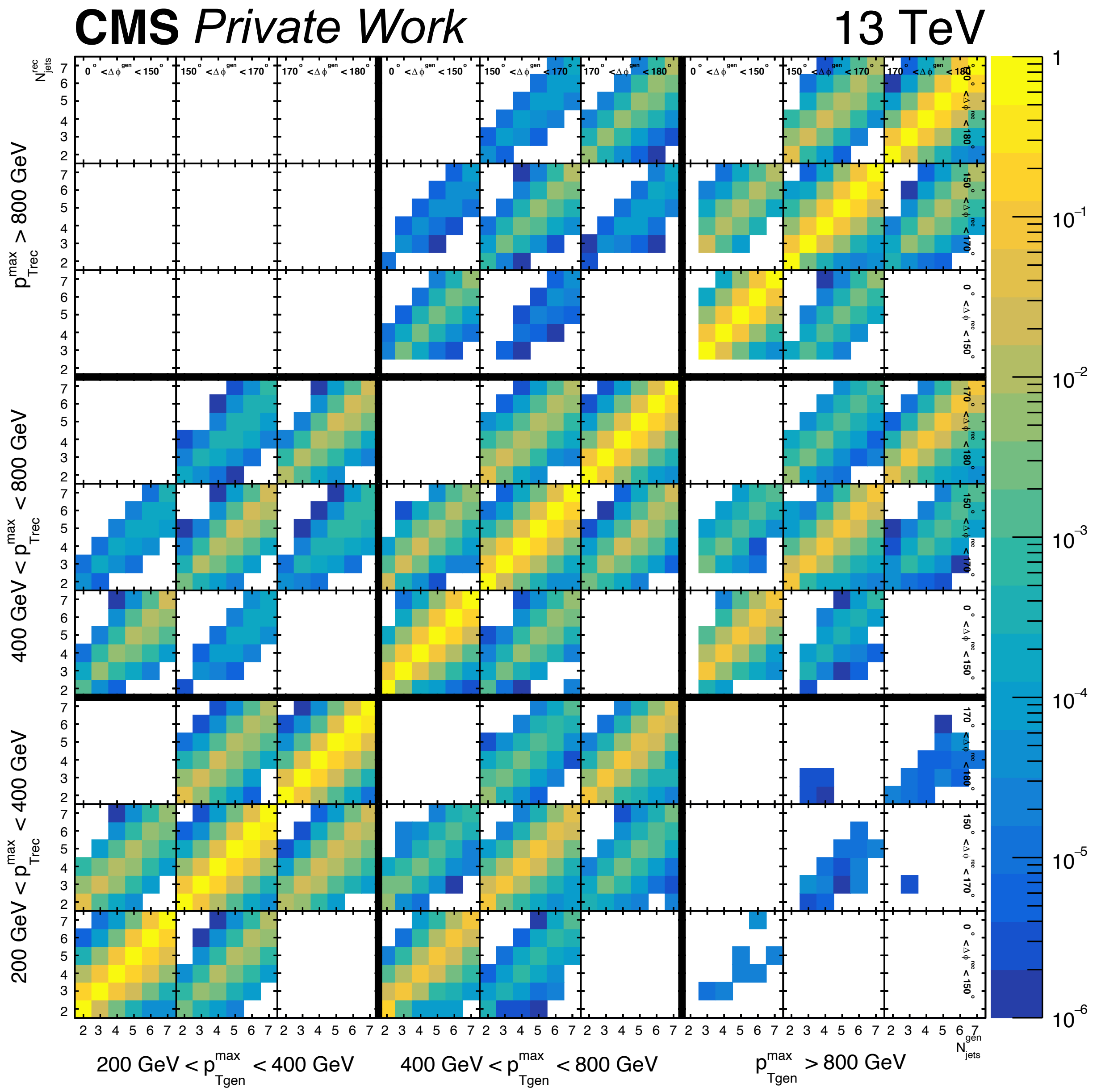
Unfolding

3D Jet multiplicity distribution

- The Response Matrix (RM) is constructed by matching dijet system in ΔR (both jets are matched within $\Delta R < 0.2$), unmatched events contribute to background and inefficiencies. From RM by normalizing to gen (hadron level) axis we get the Probability Matrix ($\mathbf{A}$). (see figure).

- Given the good condition number = 3.0 (< 10) of the $\mathbf{A}$ matrix, we unfold with real matrix inversion using TUnfold [8] (no regularization used):

$$\chi^2 = \min(\mathbf{x}) \left[(\mathbf{y} - \mathbf{b} - \mathbf{A}\mathbf{x})^{\mathrm{T}} \mathbf{V}_{\mathbf{yy}}^{-1} (\mathbf{y} - \mathbf{b} - \mathbf{A}\mathbf{x}) \right]$$

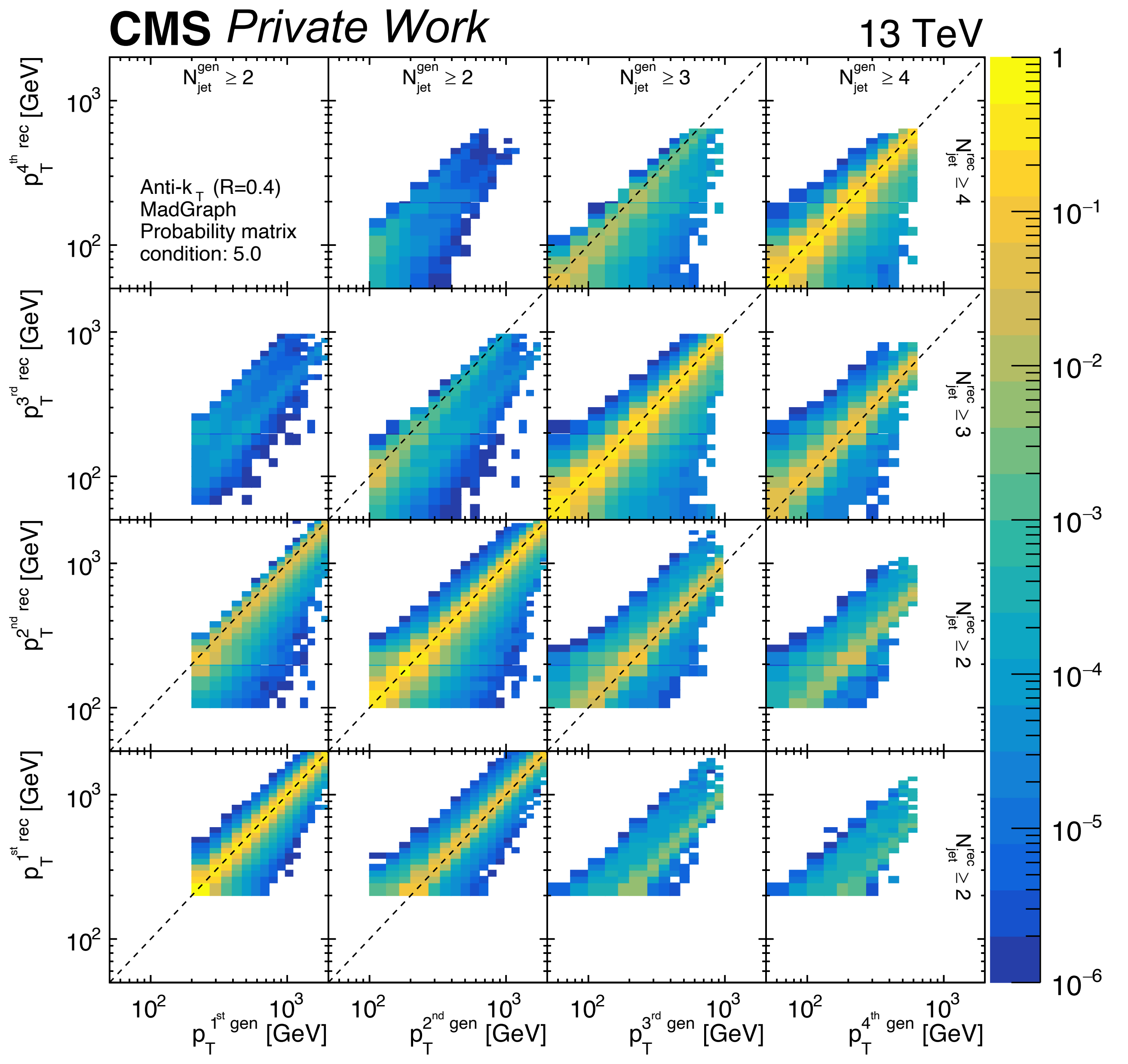


[8] https://doi.org/10.1088/1748-0221/7/10/T10003

Unfolding

2D p_T spectra of 4 first leading jets

- The RM is constructed requiring a dijet system and matching each jet in ΔR and p_T
- Probability Matrix has a good condition number = 5.0 (<10) suited for real inversion, but pseudo inversion gives more stable behavior of the systematic uncertainties (see slide 8).
- TUnfold method, with pseudo-inversion (no Tikhonov regularization) is used.



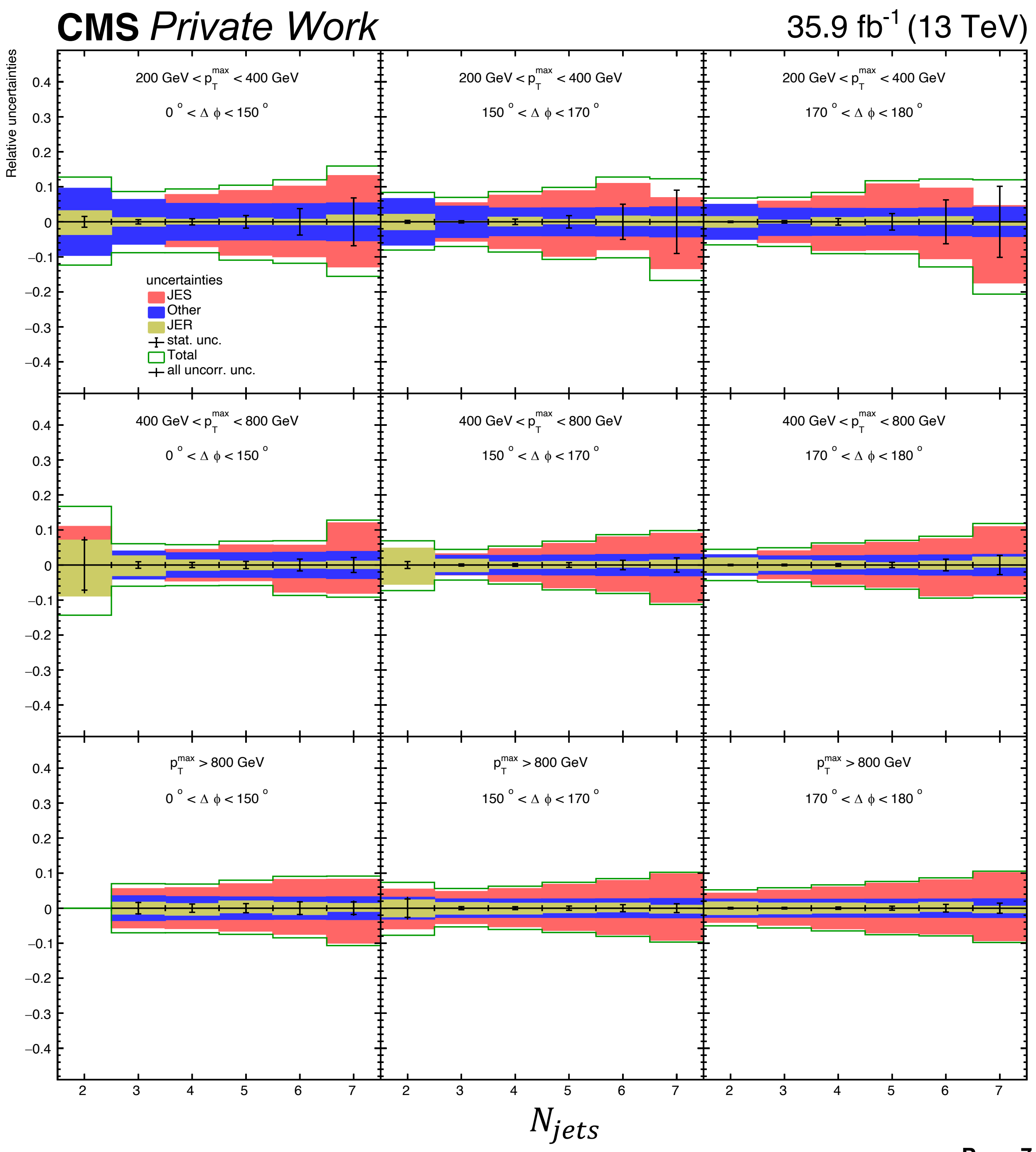
Uncertainties

Differential cross section as function of N_{jets}

- Sources of uncertainty:
  - JES coming from variations in data rec level
  - JER variations on MC response matrices
  - Other (lumi ⊕ model : { background ⊕ inefficeincies ⊕ hard scale reweighting } ⊕ prefiring)
  - Stat. unc (data)
  - All uncorr. Unc (data ⊕ MC statistics)

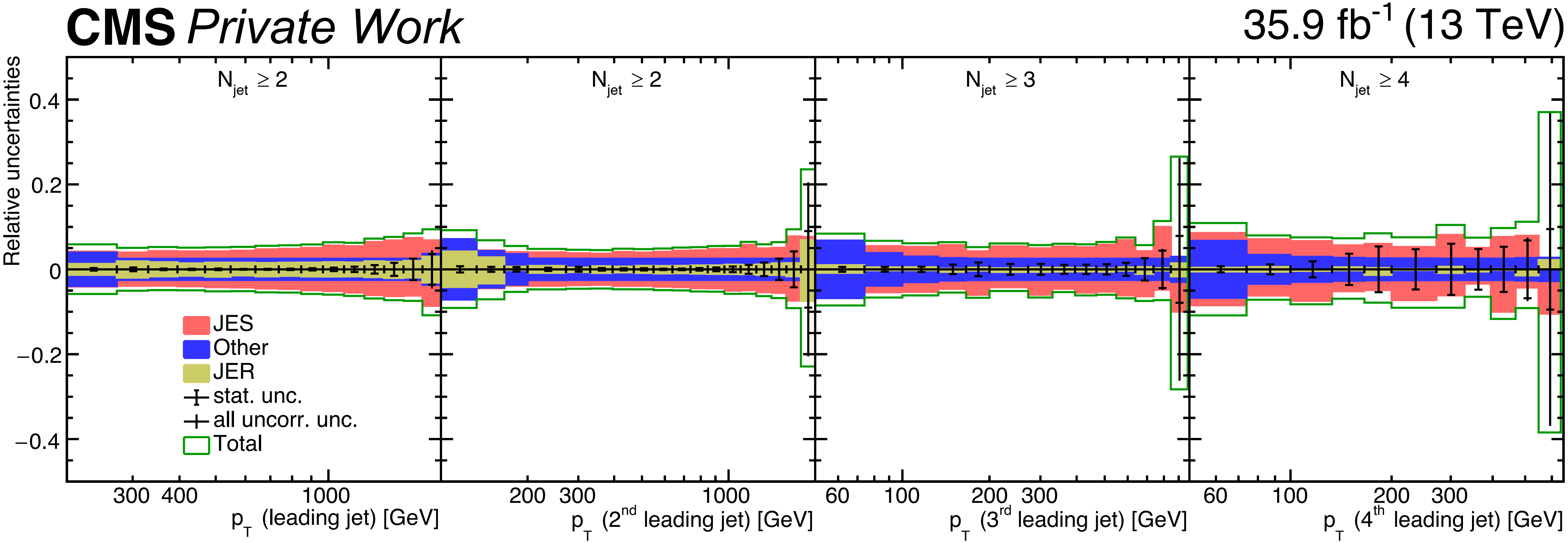
- Dominant uncertainty is JES.

- Nice behavior of the total uncertainty always around minimum of 5-10% and maximum of 10-15% even being this an (absolute) triple differential cross section.



Uncertainties

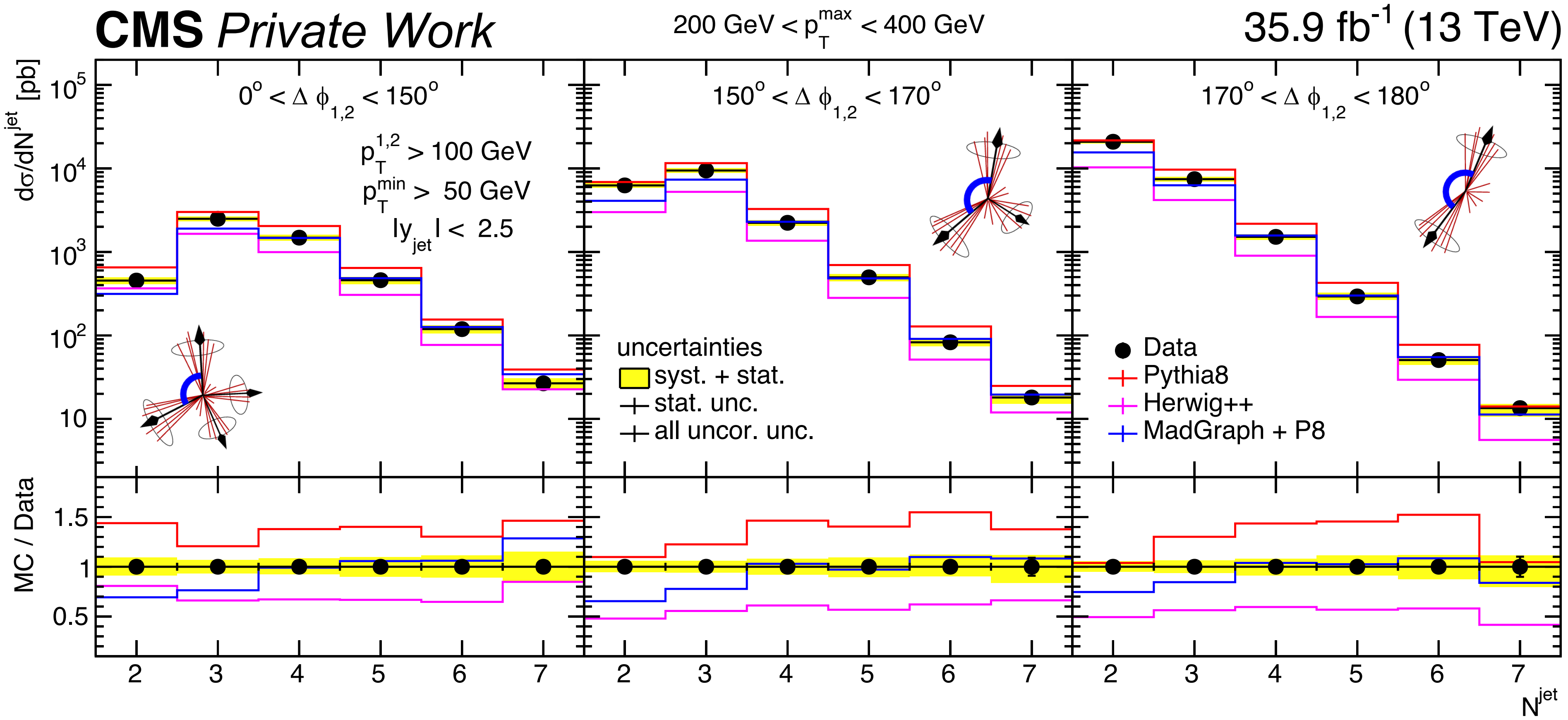
Differential p_T cross sections of 4 first leading jets



- The use of pseudo-inversion has reduced the statistical uncertainties, also systematics as JES has better behavior specially for the 4th jet p_T , compared to the use of real-inversion (real-inversion result not shown here)

Results

Differential cross section as function of the jet multiplicity compared to LO MC predictions

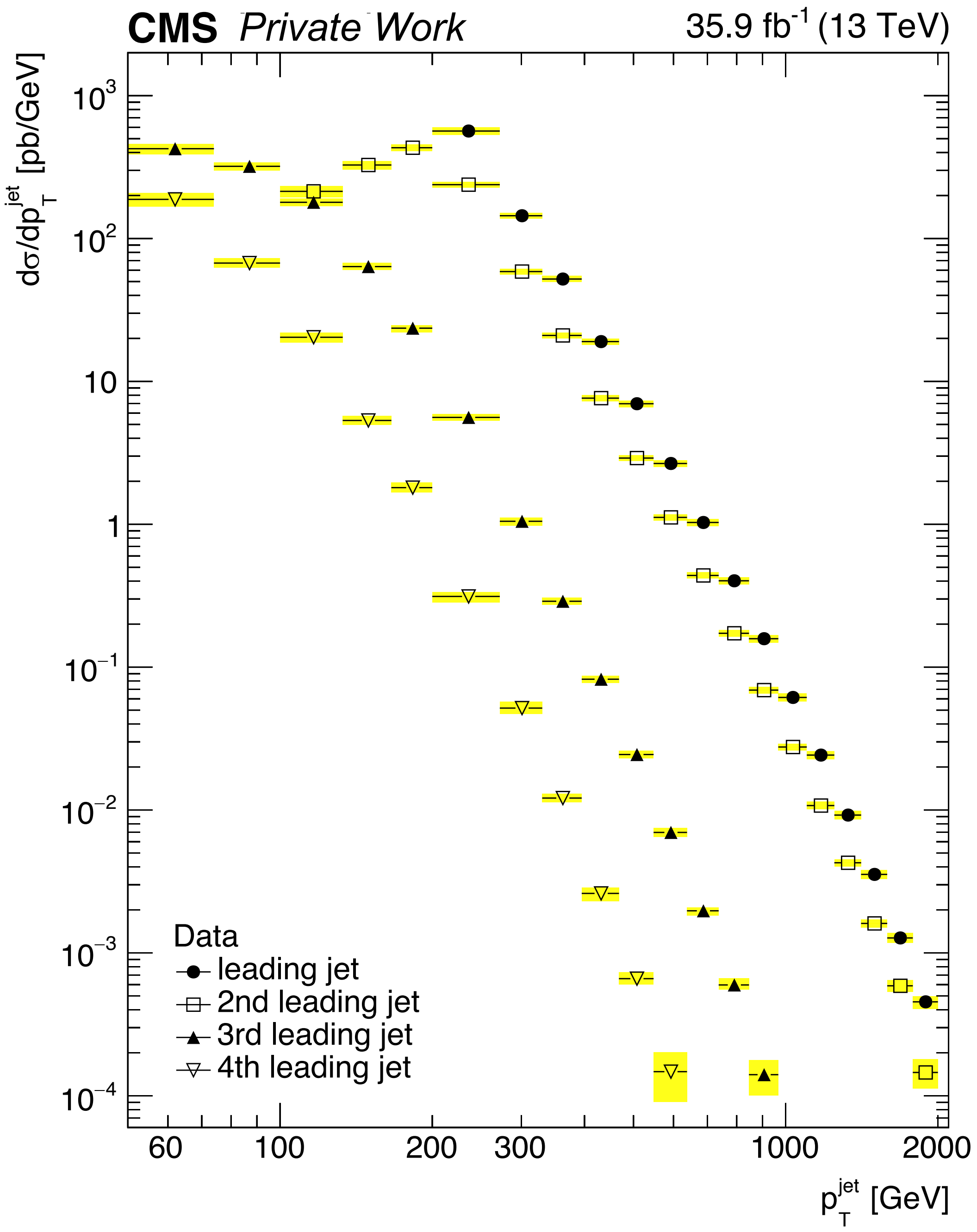


- Better description from MadGraph+P8 due to better LO matrix element calculation (2->2 2->3 2->4)
- In the back-to-back Herwig++ describes better the shape of the data distribution wrt. Pythia8.

Results

Differential p_T cross sections of 4 first leading jets

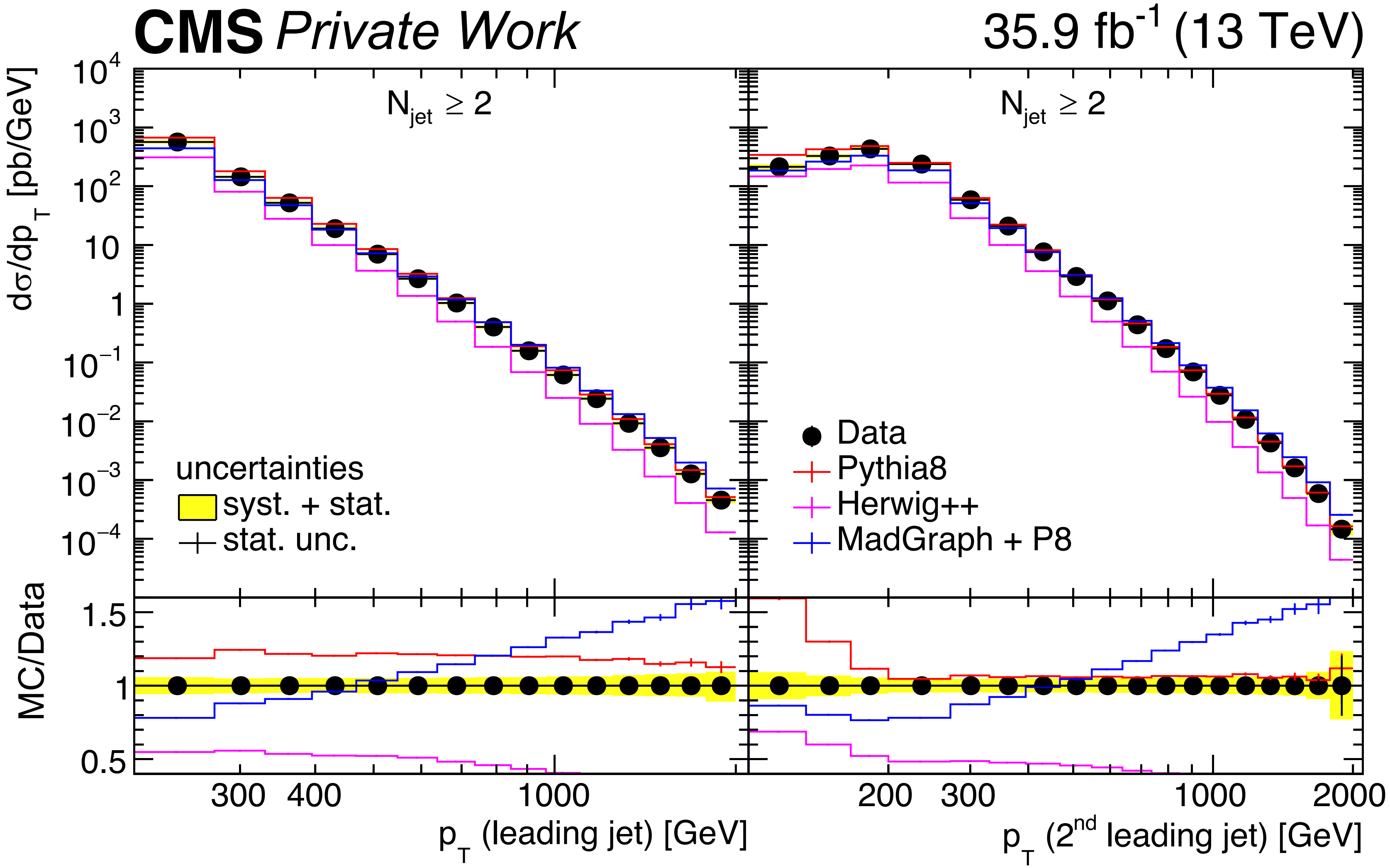
- Measured p_T of the first four leading jet is shown. In the plot, the yellow band represents the total experimental uncertainty.
- The effect of the different p_T cuts on leading (p_T > 200 GeV) and 2nd leading jet (p_T > 100 GeV) is observed.
- The cross sections for leading and 2nd leading jet are of the same order, falling fore more than 7 orders of magnitude.
- The spectrum becomes more steeply falling for 3rd and 4th leading jets (p_T > 50 GeV).



Results

Differential p_T cross sections of the 2 first leading jets compared to LO MC predictions

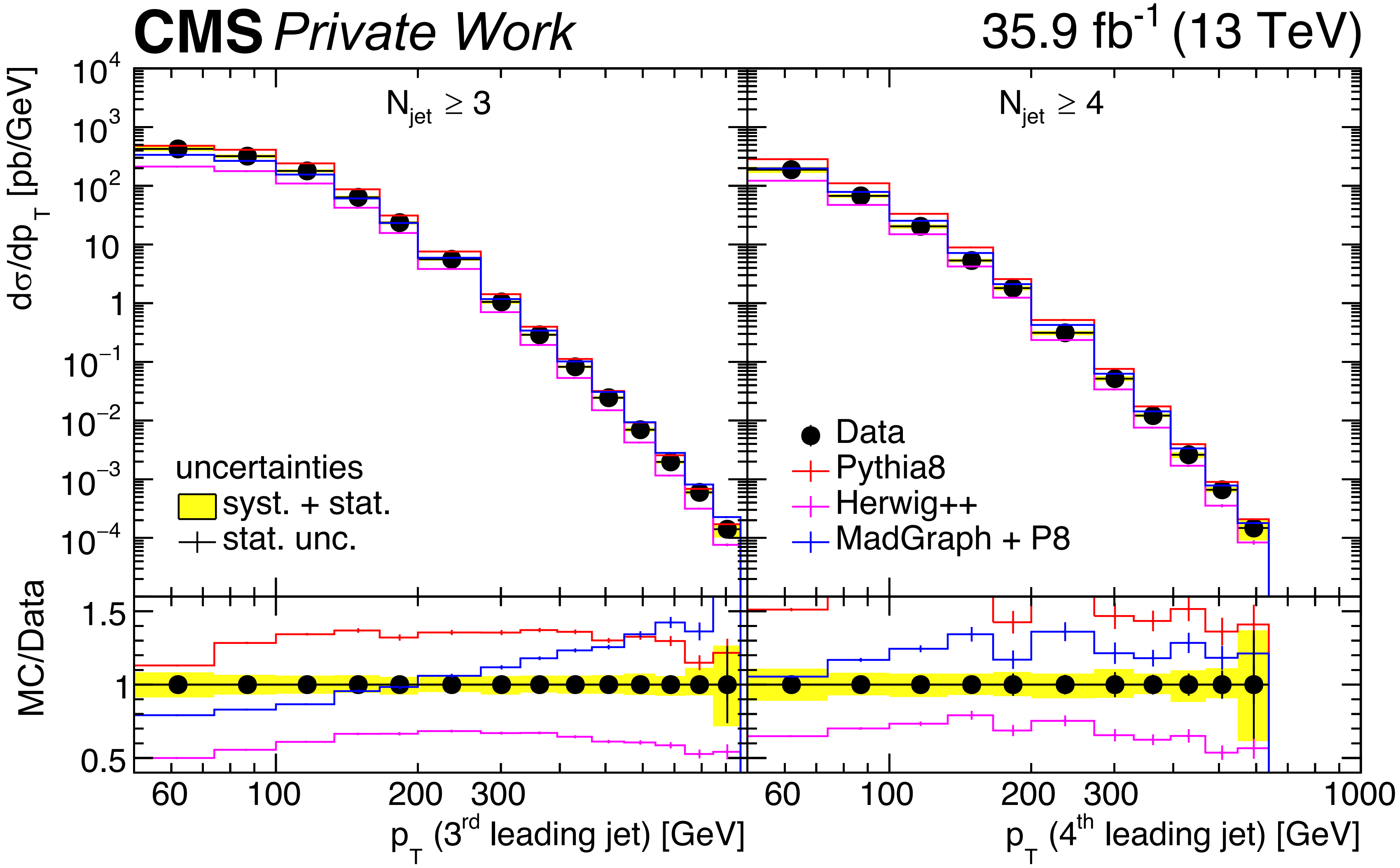
- MadGraph sample (up to 4 patrons in the final state) is not able to describe the data.
- Pythia8 can describe the data better than Herwig in normalization.
- None of the predictions is consistent describing the dijet system p_T.



Results

Differential p_T cross sections of the extra jets compared to LO MC predictions

- Description from MadGraph have different ratios for 3rd and 4th leading jets.
- Herwig and Pythia8 do not describe the data in normalization.
- None of the predictions is consistent describing the extra jets p_T.



Summary

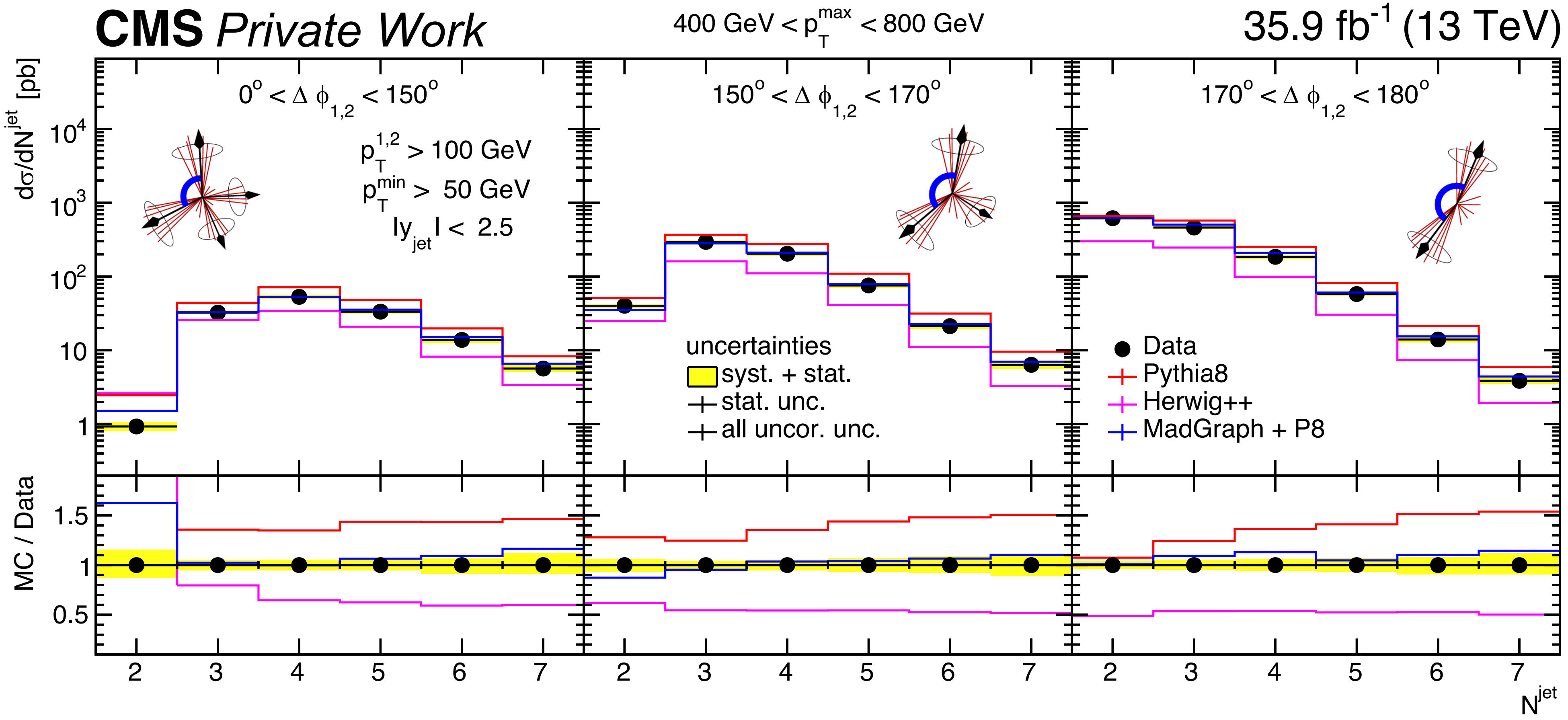
- Dijet multi-differential cross sections measured :
  - Jet Multiplicity (N_{jets},$\Delta\phi_{dijet}$, p_T^{max}).
  - p_T spectra of 4 first leading jets (p_T^i , N_{jet}^i).

- Comparisons to LO MC were performed.
  - None of the MCs can describe simultaneously the jet multiplicity and p_T distributions.

Thank you for your attention !

BACK UP SLIDES

Jet multiplicity distribution: Data to MC comparison



- Nice description from MadGraph due to better LO matrix element calculation (2->2   2->3 2->4)
- In the back-to-back region we can see a very nice shape description of the data from Herwig.

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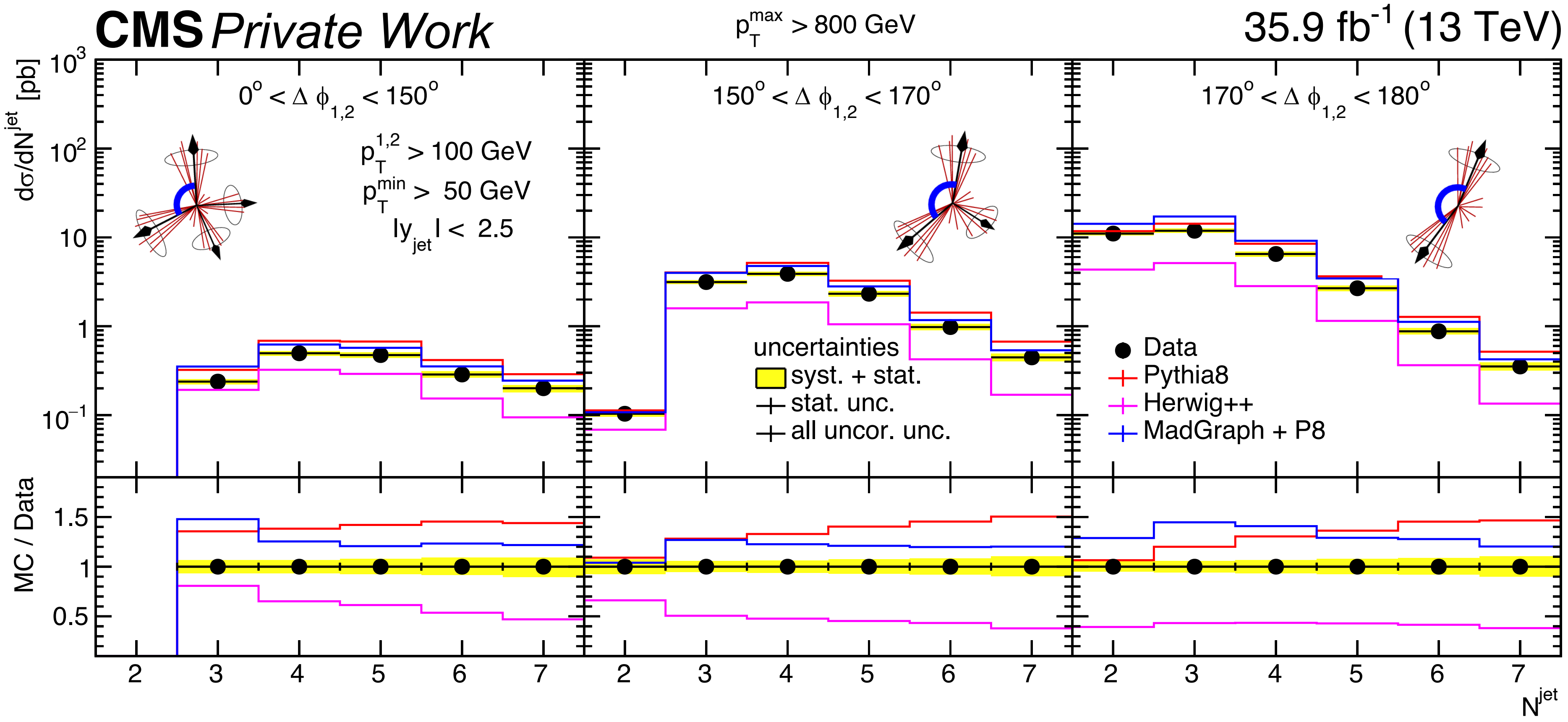
Jet multiplicity distribution: Data to MC comparison



- This region of the phase space is very interesting since even MadGraph fails in the normalization.
- Regardless the normalization still in the back-to-back region we can see a very nice shape description of the data from Herwig++.

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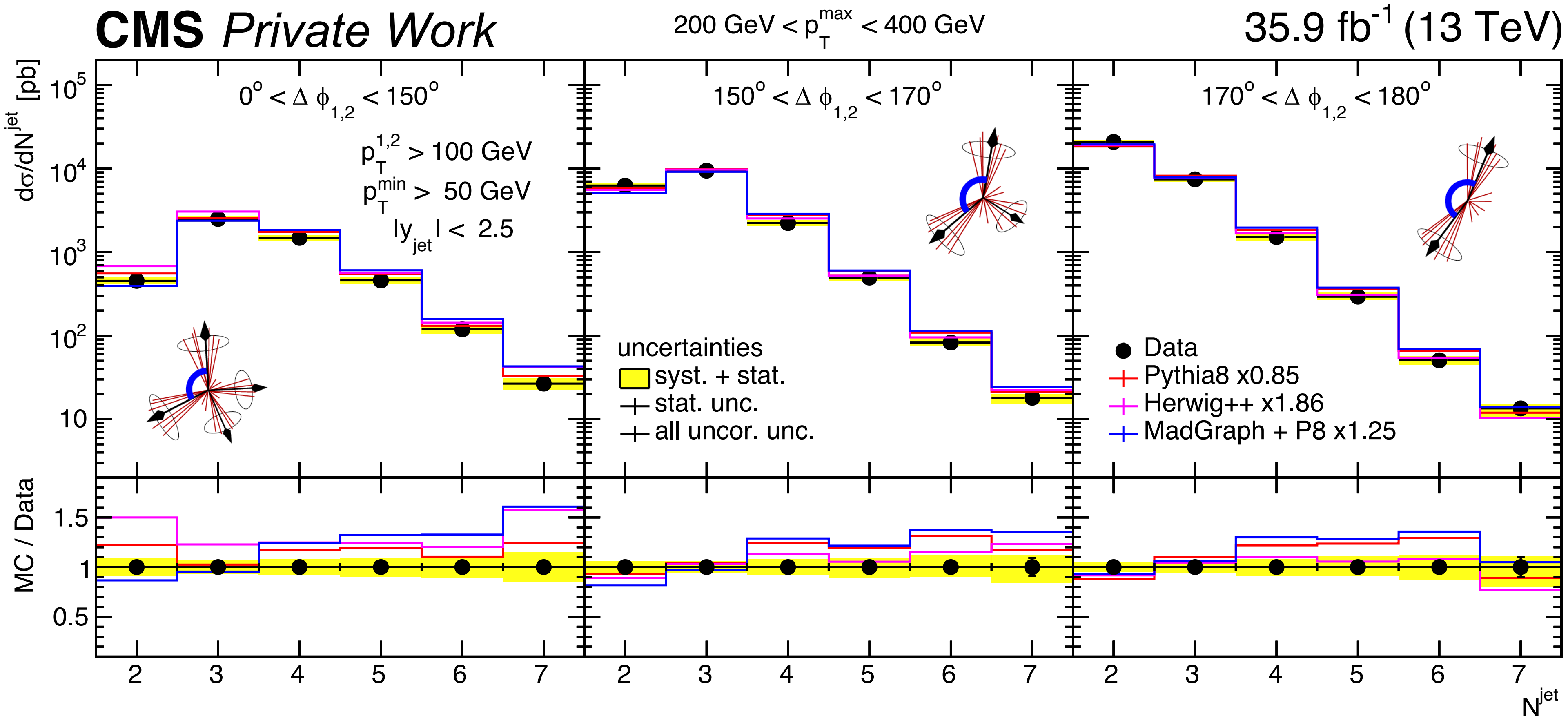
Jet multiplicity distribution : MC normalized to data cross section



- Here we can see nice shape description from Herwig++ (especially on the back-to-back region)
- Pythia8 and MadGraph+P8 fail to describe the shape of the distribution.

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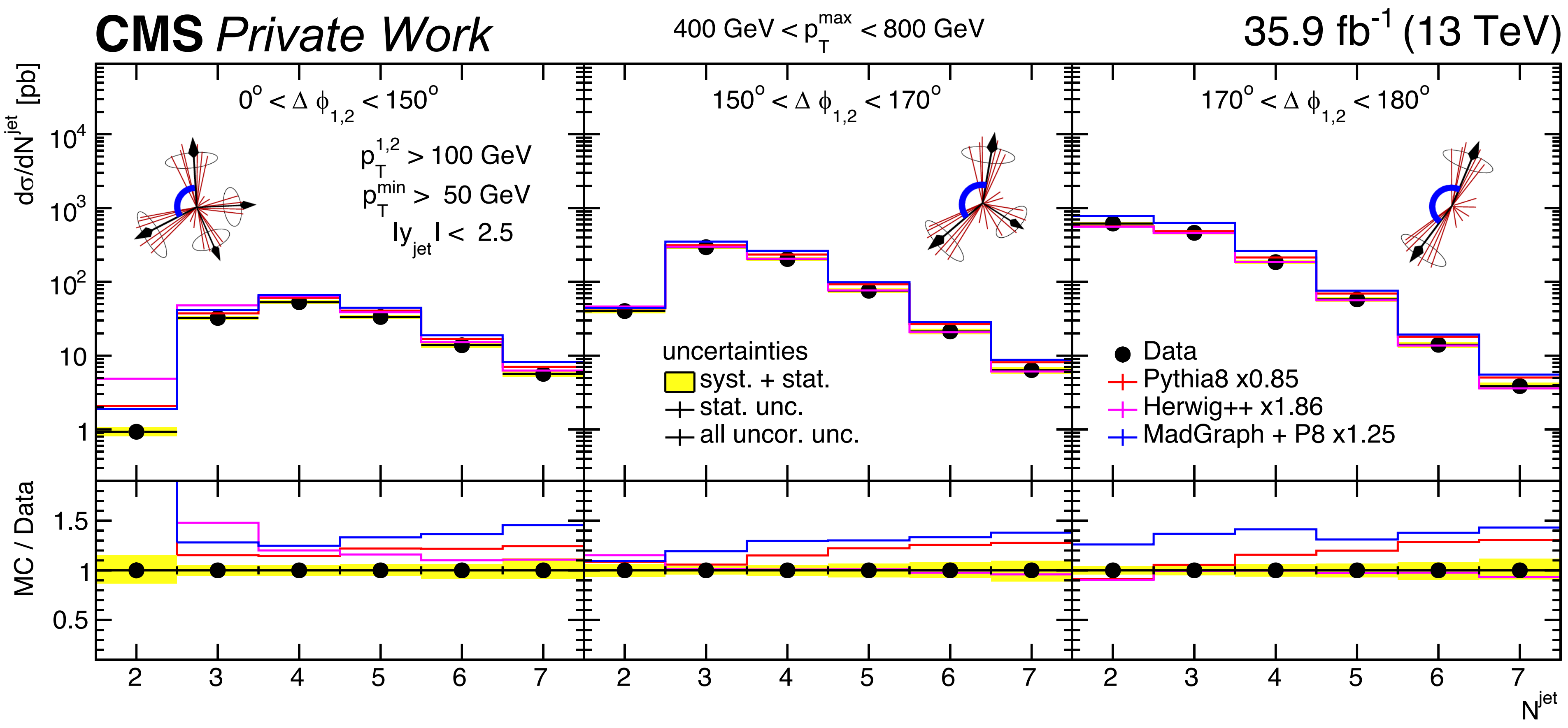
Jet multiplicity distribution : MC normalized to data cross section



- ➢ Here we can see nice shape description from Herwig++ (especially on the back-to-back region)
- ➢ Pythia8 and MadGraph+P8 fail to describe the shape of the distribution.

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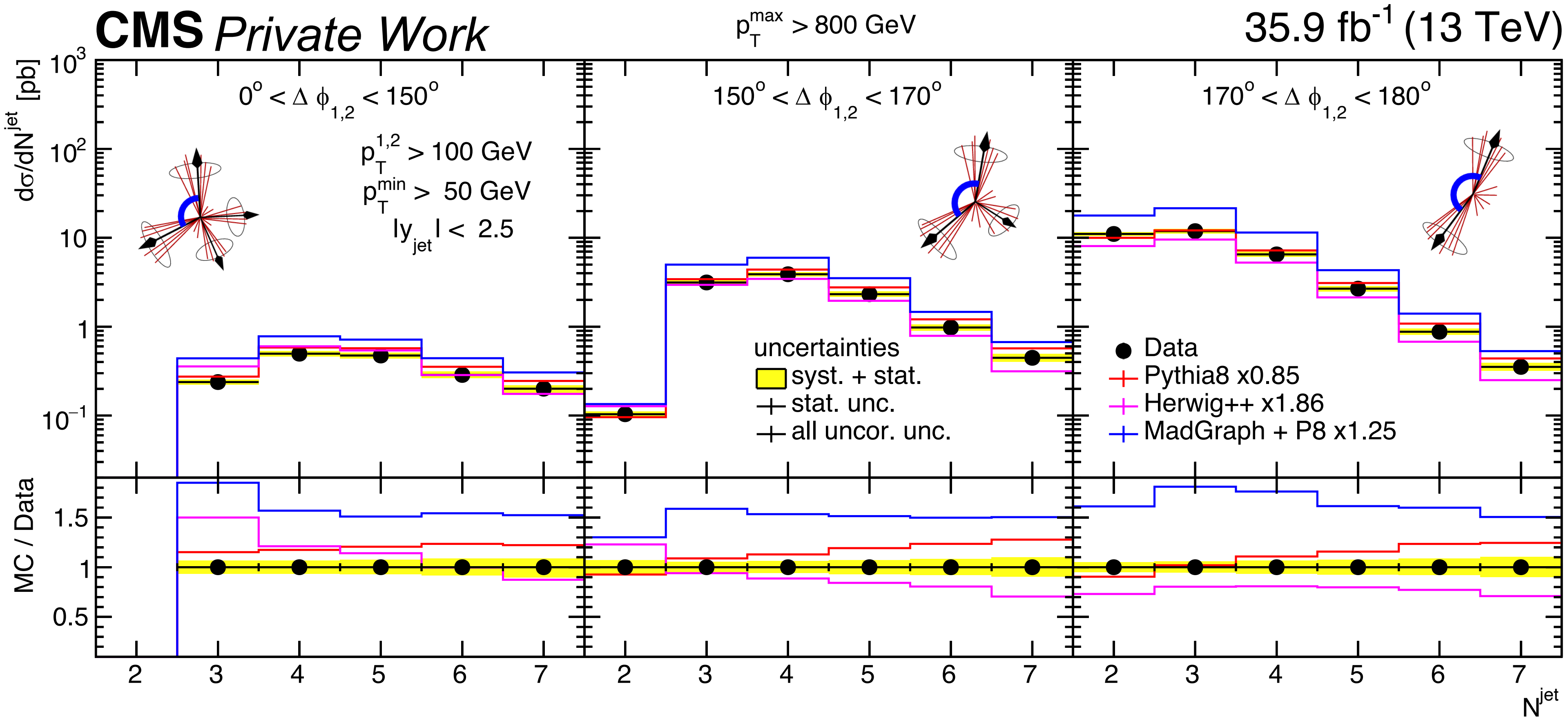
Jet multiplicity distribution : MC normalized to data cross section



- Here we can see nice shape description from Herwig++ (especially on the back-to-back region)
- Pythia8 and MadGraph+P8 fail to describe the shape of the distribution.

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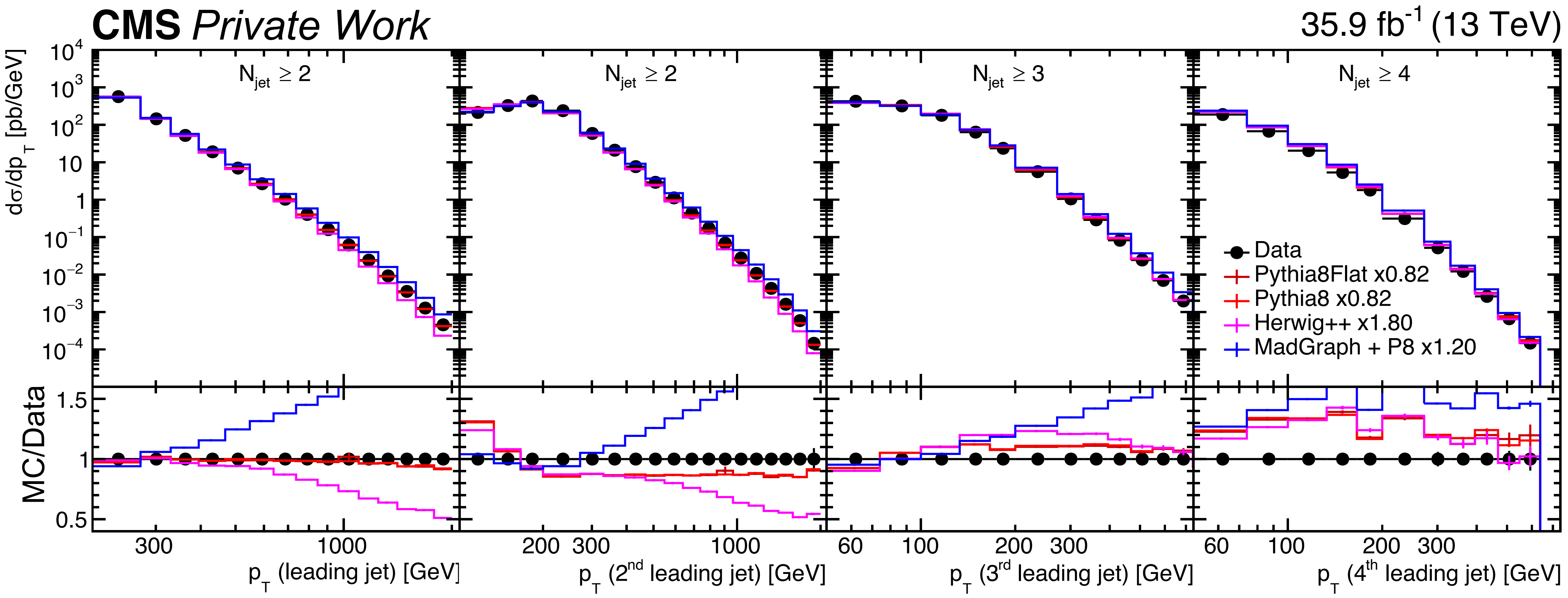
p_T spectra of first 4 leading jets : MC normalized to data cross section (only stat. unc. Is shown)



- ➢ Here for leading and 2nd leading jets we can observe a better shape description from Pythia8, Herwig++ is similar up to 500 GeV (this mainly is given due to the different PDFs used).
- ➢ For 3rd and 4th leading jets Pythia8 and Herwig++ show similar description, acceptable for 3rd jet but already for the 4th jet the MCs are not able to describe the data (these jets come from the shower)

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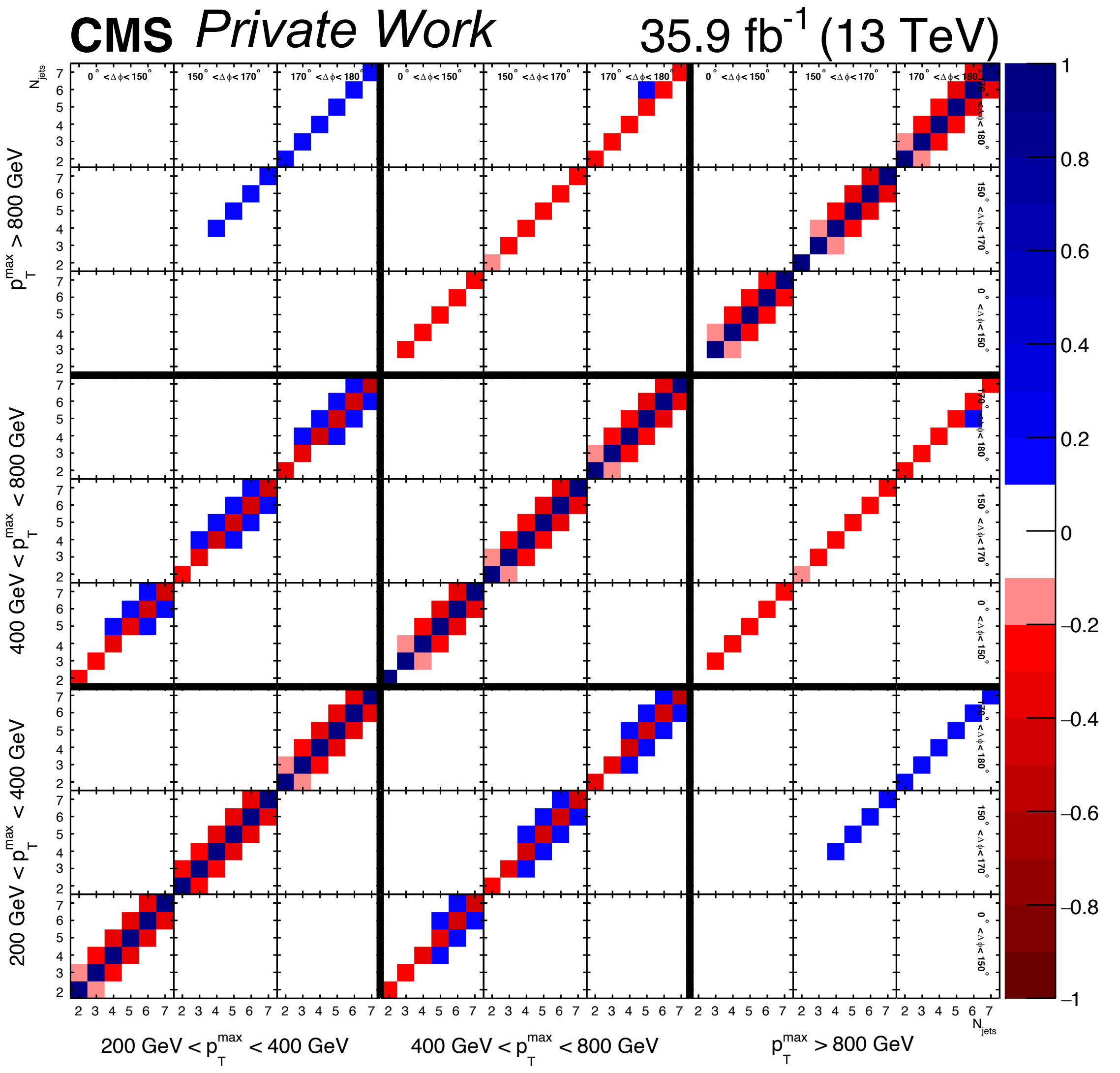
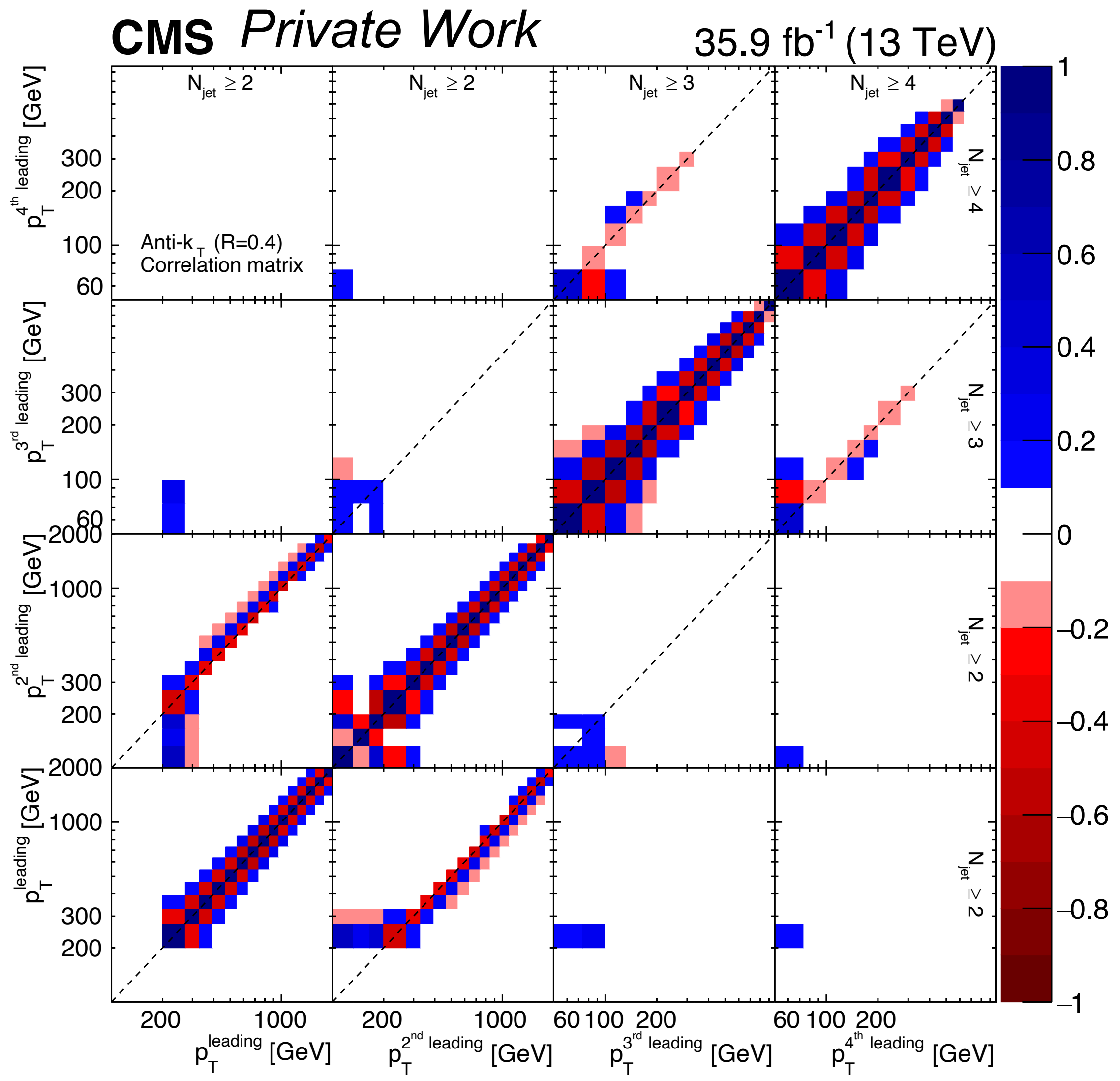
Statistical correlations (Correlation Matrix) -> Jet multiplicity (left plot) p_T distributions (right plot)





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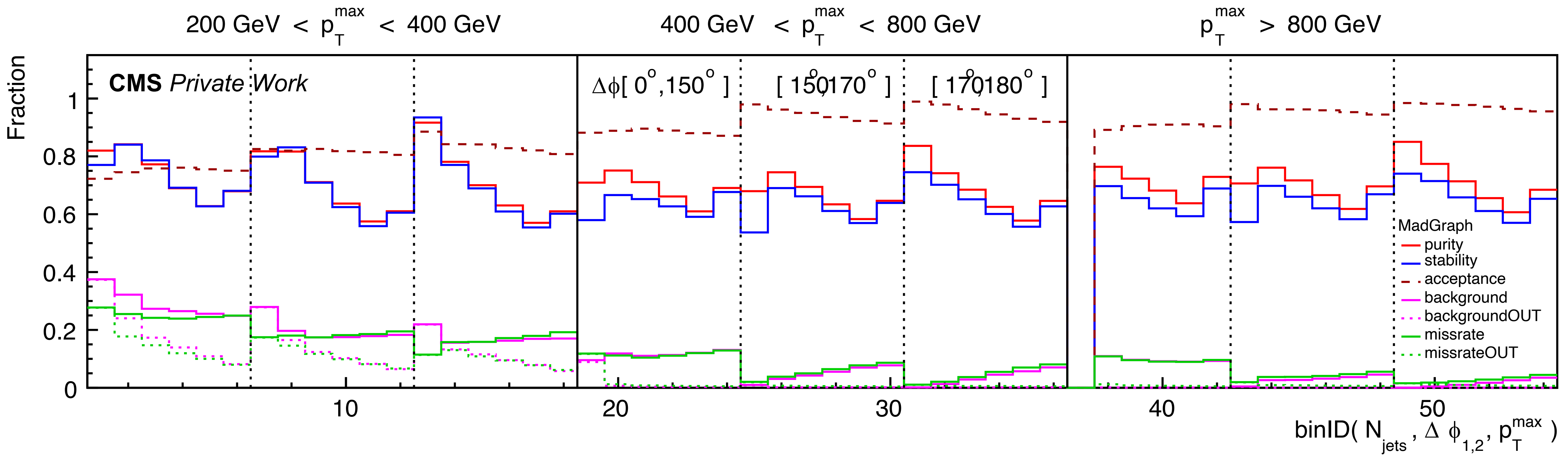
Multiplicity distribution: purity, stability, acceptance, background and missrate (inefficiencies)



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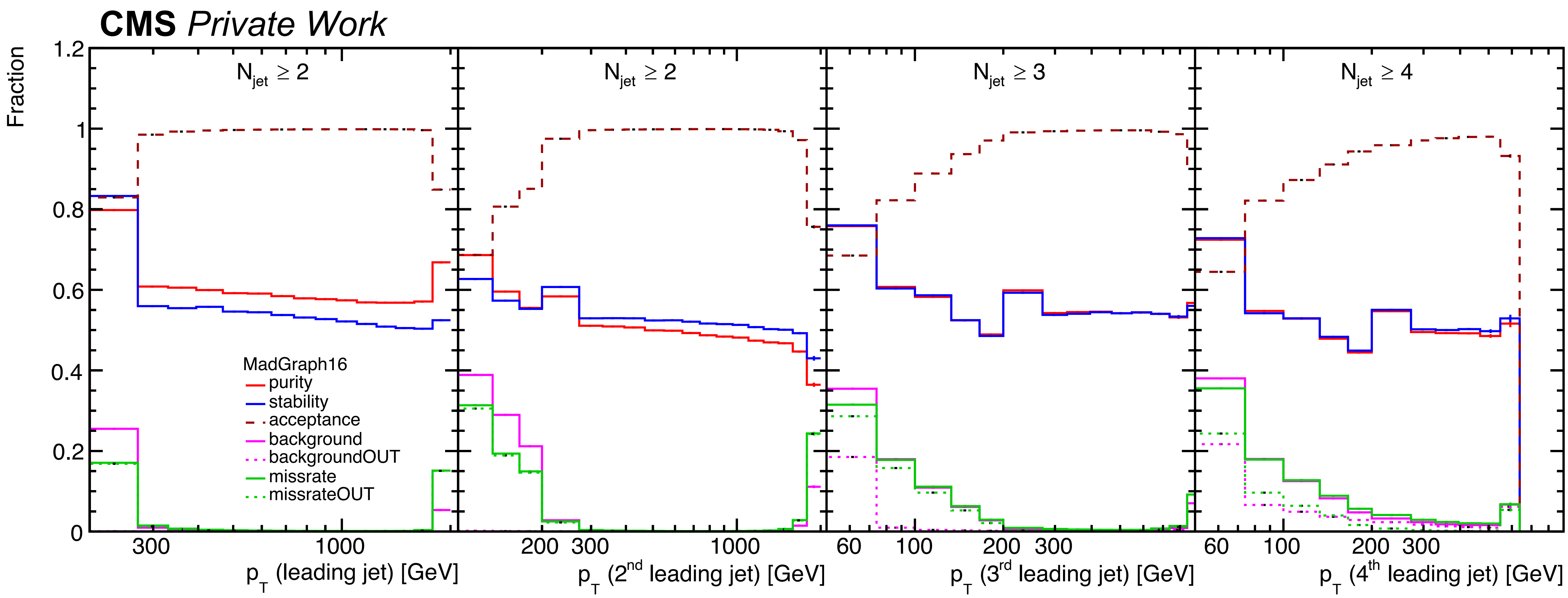
p_T spectra of 4 first leading jets : purity, stability, acceptance, background and missrate (inefficiencies)



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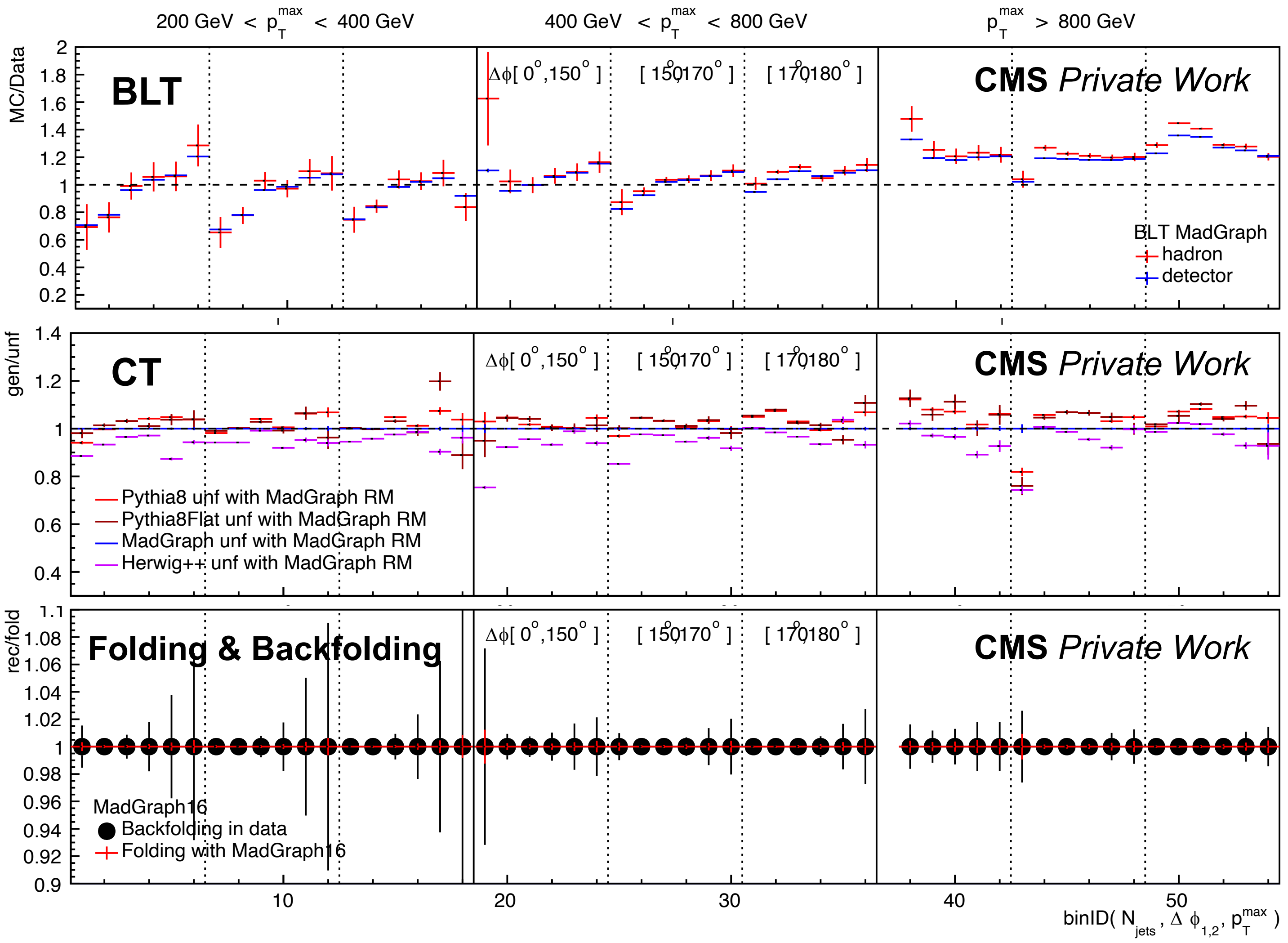
Unfolding tests for Jet multiplicity



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Unfolding tests for p_T of the first 4 leading jets